HUBBLE TROUBLE

How a recharged debate over the expansion of the universe could lead to new physics

By **Joshua Sokol**

It was the early 1990s, and the Carnegie Observatories in Pasadena, California, had emptied out for the Christmas holiday. Wendy Freedman was toiling alone in the library on an immense and thorny problem: the expansion rate of the universe.

Carnegie was hallowed ground for this sort of work. It was here, in 1929, that Edwin Hubble first clocked faraway galaxies flying away from the Milky Way, bobbing in the outward current of expanding space. The speed of that flow came to be called the Hubble constant.

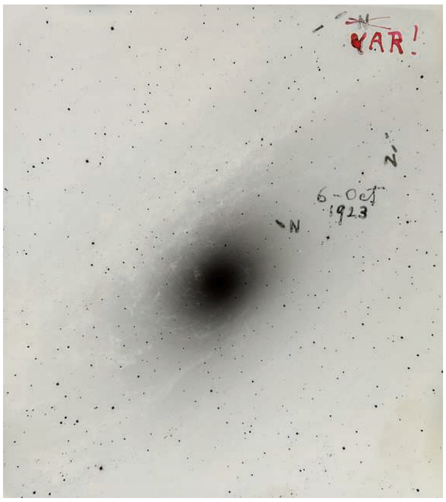
Freedman's quiet work was soon interrupted when fellow Carnegie astronomer Allan Sandage stormed in. Sandage, Hubble's designated scientific heir, had spent decades refining the Hubble constant, and had consistently defended a slow rate of expansion. Freedman was the latest challenger to publish a faster rate, and Sandage had seen the heretical study.

"He was so angry," recalls Freedman, now at the University of Chicago in Illinois, "that you sort of become aware that you're the only two people in the building. I took a step back, and that was when I realized, oh boy, this was not the friendliest of fields."

The acrimony has diminished, but not by much. Sandage died in 2010, and by then most astronomers had converged on a Hubble constant in a narrow range. But in a twist Sandage himself might savor, new techniques suggest that the Hubble constant is 8% lower than a leading number. For nearly a century, astronomers have calculated it by meticulously measuring distances in the nearby universe and moving ever farther out. But lately, astrophysicists have measured the constant from the outside in, based on maps of the cosmic microwave background (CMB), the dappled afterglow of the big bang that is a backdrop to the rest of the visible universe. By making assumptions about how the push and pull of energy and matter in the universe have changed the rate of cosmic expansion since the microwave background was formed, the astrophysicists can take their map and adjust the Hubble constant to the present-day, local universe. The numbers should match. But they don't.

It could be that one approach has it wrong. The two sides are searching for flaws in their own methods and each other's alike, and senior figures like Freedman are racing to publish their own measures. "We don't know which way this is going to land," Freedman says.

But if the disagreement holds, it will be a crack in the firmament of modern cosmology. It could mean that current theories are missing some ingredient that intervened between the present and the ancient past, throwing off the chain of inferences from the CMB to the current Hubble constant. If so, history will be repeating itself. In the 1990s, Adam Riess, now an astrophysicist at Johns Hopkins University in Baltimore, Maryland, led one of the groups that discovered dark energy, a repulsive force that is accelerating the expansion of the universe. It is one of the factors that the CMB calculations must take into account.



A 1923 image of the Andromeda galaxy. A cepheid, or variable star (marked VAR!), helped Edwin Hubble determine the vast distance to Andromeda.

Now, Riess's team is leading the quest to pin down the Hubble constant in nearby space and beyond. His goal is not just to refine the number, but to see whether it is changing over time in ways that even dark energy—as currently conceived—can't explain. So far, he has few hints about what the missing factor might be. "I'm really wondering what is going on," he says.

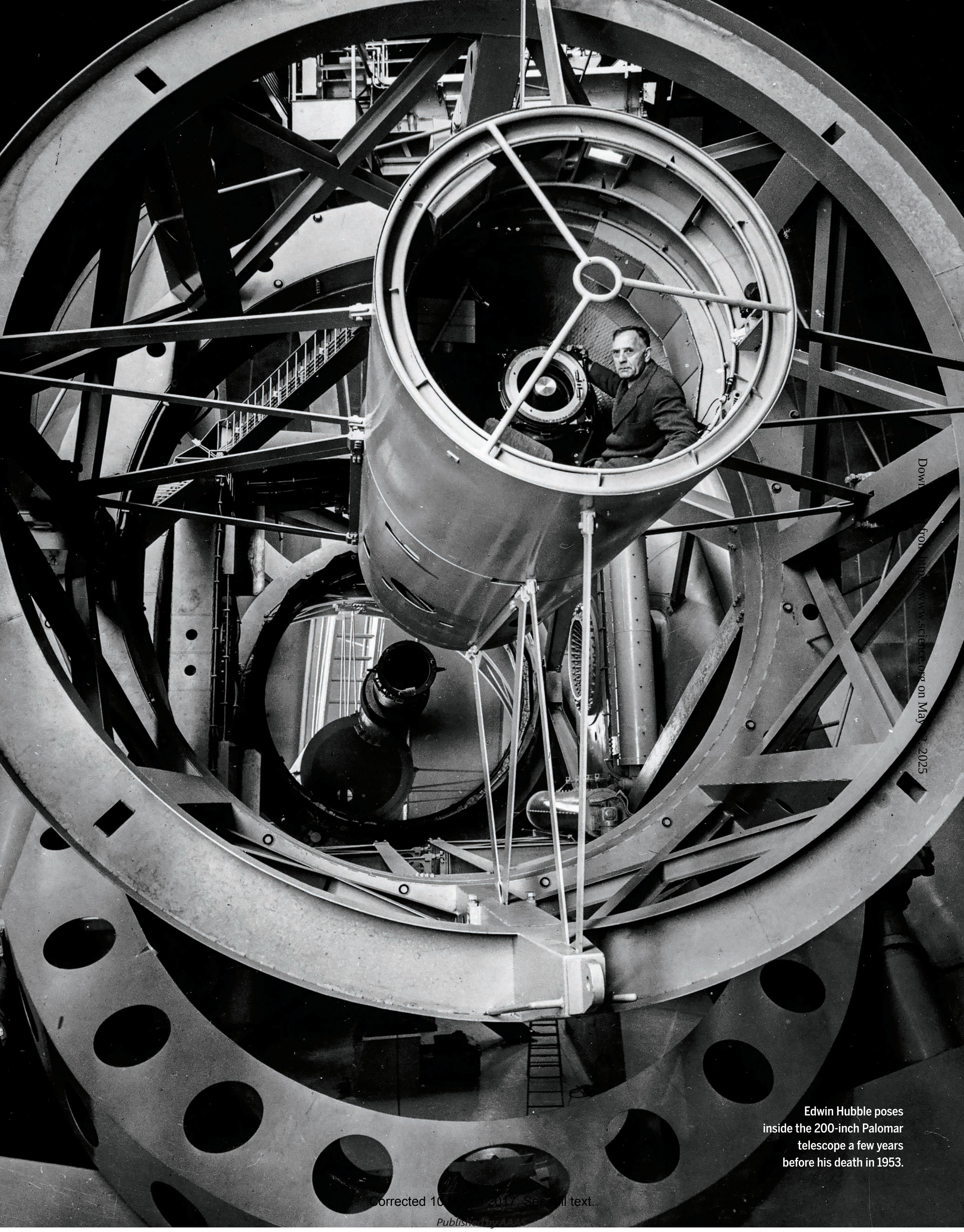
IN 1927, Hubble was moving beyond the Milky Way with what was then the world's biggest telescope, the 100-inch (2.5-m) Hooker telescope that loomed over Pasadena on top of Mount Wilson. He photographed the faint spiral smudges we know as galaxies and measured the reddening of their light as their motions Doppler-shifted it to longer wavelengths, like the keening of a receding ambulance. By comparing the galaxies' redshifts to their brightness, Hubble stumbled on something revolutionary: The dimmer and presumably farther away a galaxy was, the faster it was receding. That meant the universe was expanding. It also meant the universe had a finite age, beginning in a big bang.

To pin down the expansion rate—his eponymous constant—Hubble needed actual distances to the galaxies, not just relative ones based on their apparent brightness. So he began the laborious process of building up a distance ladder—from the Milky Way to neighboring galaxies to the far reaches of expanding space. Each rung in the ladder has to be calibrated by "standard candles": objects that shift, pulse, flash, or rotate in a way that reliably encodes how far away they are.

The first rung seemed reasonably sturdy: variable stars called cepheids, which ramp up and down in brightness over the course of days or weeks. The length of that cycle indicates the star's intrinsic brightness. By comparing the observed brightness of a cepheid to the brightness inferred from its oscillations, Hubble could gauge its distance. The Mount Wilson telescope was only good enough to see a few cepheids in the nearest

PHOTOS: THE CARNEGIE OBSERVATORIES; (OPPOSITE PAGE) J. R. EYERMAN/THE LIFE PICTURE COLLECTION/GETTY IMAGES

Corrected 10 March 2017. See full text.
Published by AAAS



Edwin Hubble poses inside the 200-inch Palomar telescope a few years before his death in 1953.

galaxies. For more distant galaxies, he assumed that the brightest star in each had the same intrinsic brightness. Even farther out, he assumed that entire galaxies were standard candles, with uniform luminosities.

They weren't good assumptions. Hubble's first published constant was 500 kilometers per second per megaparsec—meaning that for every 3.25 million light-years he looked out into space, the expanding universe was ferrying away galaxies 500 kilometers per second faster. The number was way off—an order of magnitude too fast. It also implied a universe just 2 billion years old, a baby compared with current estimates. But it was a start.

By 1949, construction had finished on the 200-inch (5.1-m) telescope at Palomar in southern California—just in time for Hubble to suffer a heart attack. Hubble passed the mantle to Sandage, an ace observer who spent the subsequent decades exposing photographic plates during all-night sessions suspended in the telescope's vast apparatus, shivering and in desperate need of a bathroom break.

With Palomar's higher resolution and light-gathering power, Sandage could pluck cepheids from more distant galaxies. He also realized that Hubble's bright stars were in fact entire star clusters. They were intrinsically brighter and thus farther away than Hubble thought, which, in addition to other corrections, implied a much lower Hubble constant. By the 1980s, Sandage had settled on a value of about 50, which he zealously defended. Perhaps his most famous foil, French astronomer Gérard de Vaucouleurs, promoted a competing value of 100. One of the key parameters of cosmology was contested to an embarrassing factor of two.

In the late 1990s, Freedman, having survived Sandage's verbal abuse, was determined to solve the puzzle with a powerful new tool designed with just this job in mind: the Hubble Space Telescope. Its sharp view from above the atmosphere allowed Freedman's team to pick out individual cepheids up to 10 times farther away than Sandage had with Palomar. Sometimes those galaxies happened to host both cepheids and an even brighter beacon—a type Ia supernova. These exploding white dwarf stars are visible across space and flare to a consistent, maximum brightness. Once calibrated with the cepheids, the supernovae could be used on their own to probe the most distant reaches of space. In 2001, Freedman's team narrowed the Hubble constant to 72 plus or minus eight, a definitive effort that ended Sandage and De Vaucouleurs's feud. "I was done," she says. "I never thought I'd work on the Hubble constant again."

BUT THEN CAME THE PHYSICISTS, who had an independent way of calculating the Hubble constant with the most distant, redshifted thing of all: the microwave background. In 2003, the Wilkinson Microwave Anisotropy Probe (WMAP) published its first map showing the speckles of temperature variations on the CMB. The maps provided not a standard candle, but a standard yardstick: a pattern of hotter and colder spots in the primordial soup created by sound waves rippling through the newborn universe.

Astronomers Allan Sandage and Wendy Freedman clashed in their calculations of the Hubble constant.

With a few assumptions about the ingredients in that soup—familiar particles like atoms and photons, some extra invisible stuff called dark matter, and dark energy—the WMAP team could calculate the physical size of those primordial sound waves. That could be compared to the apparent size of the sound waves as recorded in the CMB speckles. The comparison gave the distance to the microwave background, and a value for the expansion rate of the universe at that primordial moment. By making assumptions about how regular particles, dark energy, and dark matter have altered the expansion since then, the WMAP team could tune the constant to its current rate of swelling. Initially, they came up with a value of 72, right in line with what Freedman had found.

But since then, the astronomical measurements of the Hubble constant have inched higher, even as error bars have narrowed. In recent publications, Riess has leapfrogged ahead of competitors like Freedman by using the infrared camera installed in 2009 on the Hubble Telescope, which can both pinpoint the distances to Milky Way cepheids and pick out their faraway, reddish cousins from the bluer stars that tend to surround cepheids. The most recent result from Riess's team is 73.24.

Meanwhile, Planck, a European Space Agency (ESA) mission that has imaged the CMB at higher resolution and greater temperature sensitivity, has settled on 67.8. In statistical terms, the two values are separated by a gulf of 3.4 sigma—not quite the 5 sigma that in particle physics signals a significant result, but getting there. "That, I think, is hard to explain as a statistical fluke," says Chuck Bennett, an astrophysicist at Johns Hopkins who led the WMAP team.

Each side is pointing its finger at the other. George Efstathiou, a leading cosmologist for the Planck team at the University of Cambridge in the United Kingdom, says the Planck data are "absolutely rock solid." Fresh off analyzing the first Planck results in 2013, Efstathiou cast his eyes elsewhere. He downloaded Riess's data and published his own analysis with a lower and less-precise Hubble constant. He found the astronomers' outwardly groping ladder "messy," he says.

In response, the astronomers argue that they are making an actual measurement in the present-day universe, whereas the CMB technique relies on many cosmological assumptions. If the two don't agree, they ask, why not change the cosmology? Instead, "The George Efstathious of the world moved in and said, 'I'm going to reanalyze all of your data,'" says the University of Chicago's Barry Madore, who has been Freedman's collaborator and husband since the 1980s. "So what do you do? You have to find a tiebreaker."

IN THE ASTRONOMERS' CORNER is a technique called gravitational lensing. Around a massive galaxy, gravity itself warps space,

CREDITS (TOP TO BOTTOM): (PHOTOS) THE CARNEGIE OBSERVATORIES; © YURI BELETSKY, CARNEGIE INSTITUTION FOR SCIENCE; (OPPOSITE PAGE, DATA) NED/STEER/HUCHRA/RIESS; NASA/ESA

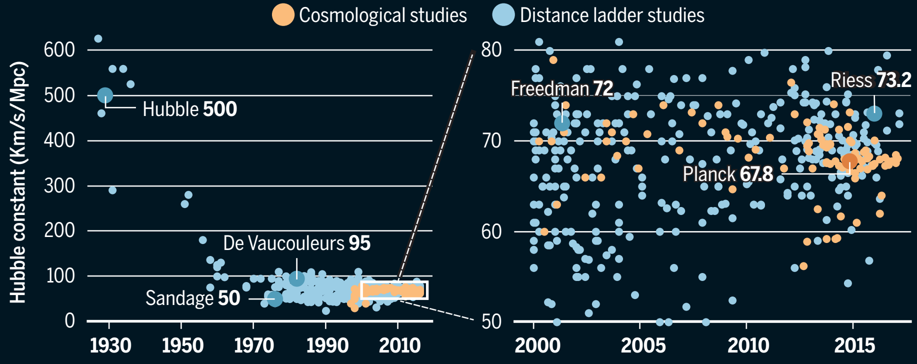
A COSMIC CONTROVERSY

By **Jia You**, **Chris Bickel**, *and* **Joshua Sokol**

Debate over the Hubble constant, the expansion rate of the universe, has exploded again. Astronomers had mostly settled on a number using a classical technique—the "distance ladder," or astronomical observations from the local universe on out. But these values conflict with cosmological estimates made from maps of the early universe and adjusted to the present day. The dispute suggests a missing ingredient may be fueling the growth of the universe.

*Data include known published Hubble constants. Cosmological studies rely at least in part on measurements of the cosmic microwave background.

Not so constant



1929
Edwin Hubble's first value was much too fast. It implied a universe that was only 2 billion years old.

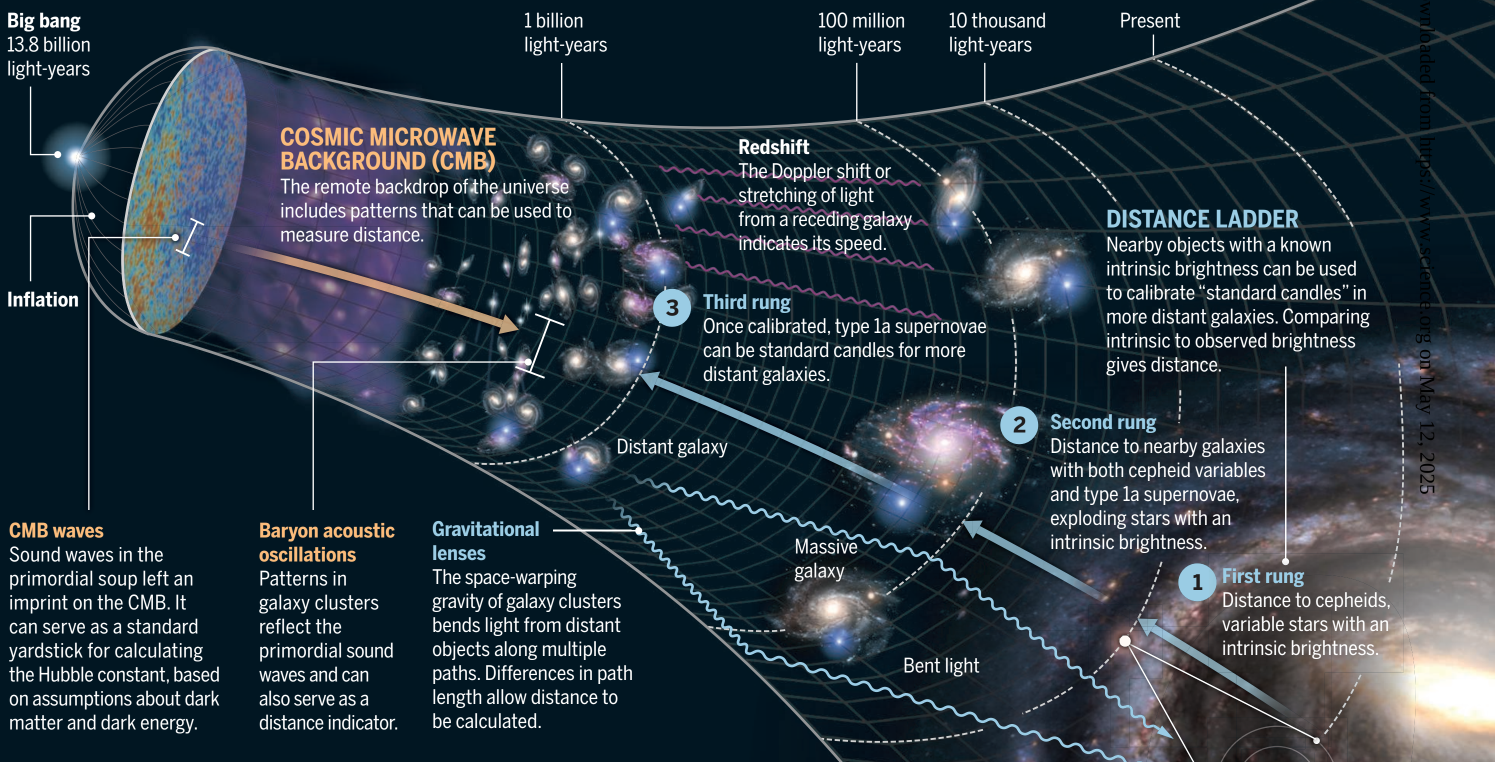
1976–1982
With the Palomar telescope, Allan Sandage found much slower rates, about half the value that his rival, Gérard de Vaucouleurs, was finding.

2001
In a prominent study, Wendy Freedman used the Hubble Space Telescope to settle on a constant of 72.

2015–Present
Debate has resumed. Adam Riess's distance ladder value is significantly higher than one derived from Planck's map of the cosmic microwave background.

Two ways to clock the cosmos

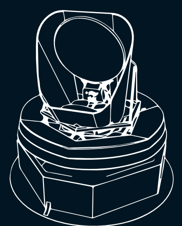
Determining the Hubble constant requires measuring the speed of receding objects and the distances to them. Speeds are easy, and come from redshifts. Distances are hard and rely on stars of known brightness or patterns of known size.



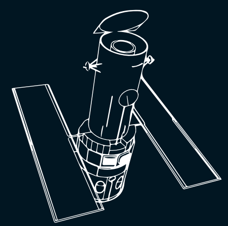
CMB waves
Sound waves in the primordial soup left an imprint on the CMB. It can serve as a standard yardstick for calculating the Hubble constant, based on assumptions about dark matter and dark energy.

Baryon acoustic oscillations
Patterns in galaxy clusters reflect the primordial sound waves and can also serve as a distance indicator.

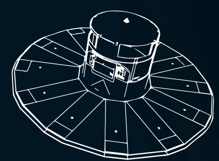
Gravitational lenses
The space-warping gravity of galaxy clusters bends light from distant objects along multiple paths. Differences in path length allow distance to be calculated.



Planck
The European telescope made high-resolution maps of the light from the CMB, which has been redshifted to cold microwave photons.



Hubble Space Telescope
By spotting cepheids and supernovae in distant galaxies, NASA's venerable telescope has firmed up the Hubble constant.



Gaia
The European telescope, in orbit around the sun beyond Earth, will triangulate to nearby cepheids, shoring up the first rung in the distance ladder.

Corrected 10 March 2017. See full text.

Published by AAAS

The South Pole Telescope will help astrophysicists map the tiny temperature variations of the cosmic microwave background, refining one Hubble measurement.

forming a giant lens that can bend light from a more distant light source, like a quasar. If the alignment of the lens and quasar is just right, the light can follow several paths to Earth, creating multiple images around the lensing galaxy. In even luckier circumstances, the quasar flickers in brightness. That causes each cloned image to flicker, too, but at different times, because the light rays for each image take different paths through the bent space. The delays between the flickers indicate differences in the path lengths; by combining those with the size of the galaxy, astronomers can use trigonometry to calculate the absolute distance to the lensing galaxy. Only three gravitational lenses have been rigorously measured this way, with six more under study now. But in late January, astrophysicist Sherry Suyu of the Max Planck Institute for Astrophysics in Garching, Germany, and her collaborators published their current best guess at the Hubble constant. "Our measurement is in agreement with the distance ladder approach," Suyu says.

The cosmologists, meanwhile, have their own sister technique: baryon acoustic oscillations (BAOs). As the universe aged, the same sound wave patterns imprinted on the CMB—the primordial yardstick—seeded the nuggets of matter that grew into galaxy clusters. The patterning of galaxies on the sky should preserve the original dimensions of the sound waves, and as before, comparing the apparent scale of the pattern to its calculated actual size leads to a distance. Like the CMB technique, the BAO method makes cosmological assumptions. But over the past few years, it has been yielding Hubble constant values in line with Planck's. The ongoing fourth iteration of the Sloan Digital Sky Survey, a vast galaxy mapping effort, should help refine these measurements.

That's not to say that the bickering distance ladder and CMB teams are simply waiting for other methods to settle the dispute. To firm up the foundation of the distance ladder, the distances to cepheids in the Milky Way, ESA's Gaia mission is trying to find precise distances to about a billion different nearby stars, cepheids included. Gaia, in orbit around the sun beyond Earth, uses the surest of all measures: parallax, or the apparent shift of the stars against the background sky, as the spacecraft swings to opposite sides of its orbit. When Gaia's full data set is released in 2022, it should provide another leap forward in certainty for the astronomers. (Already, Riess has found that his higher Hubble constant persists when he uses the preliminary Gaia results.)

The cosmologists expect to firm up their measurements, too, using the Atacama Cosmology Telescope in Chile and the South Pole Telescope, which can check Planck's high-resolution results. "It's not going to remain ambiguous," says Lyman Page, an astrophysicist at Princeton University. And if the divergent results prove rock solid, it will be up to the theorists to try to close the gap. "The gold is where the model breaks down," Page says. "Confirming the model is—blah."

ONE FIX is to add an extra particle to the standard model of the universe. The CMB offers an estimate of the overall energy budget of the universe soon after the big bang, when it was divided into matter and high-energy radiation. Because of Albert Einstein's famous equivalence $E=mc^2$, energy acted like matter, slowing the expansion of space with its gravity. But matter is a more effective brake. As time passed, radiation—photons of light and other lightweight particles like neutrinos—cooled and lost energy, diluting its gravitational influence.

There are currently three known kinds of neutrinos. If there were a fourth, as some theorists have speculated, it would have claimed a little more of the universe's initial energy budget for the radiation side, which would dissipate faster. That, in turn, would mean an early universe that expanded faster than the one predicted by standard cosmology's list of ingredients. Fast-forwarding that adjustment into the present brings the two measurements in line. Yet neutrino detectors haven't turned up any evidence for a fourth kind, and other Planck measurements put a tight cap on the total amount of surplus radiation.

Another possible fix is so-called phantom dark energy. Current cosmological models assume a constant strength for dark energy. If dark energy becomes slightly stronger over time, though, it would explain why the cosmos is expanding faster today than one might guess from looking at the early universe. But critics like Hiranya Peiris, a Planck astrophysicist based at University College London, says variable dark energy seems "ad hoc and contrived." And her work suggests that new neutrino physics doesn't work either. Right now, she says, flaws in the different techniques are more likely than new physics.

For Freedman, now a dean of the field, the only solution to the squabble is to fight fire with fire—with new observations of the universe. She and Madore are now preparing a separate measurement calibrated not just with cepheids, but other types of variable stars and bright red giants—using an automated telescope only 30 centimeters across to study the nearest examples, and the Hubble and Spitzer space telescopes to monitor them in remote galaxies. If she could handle the dark and stormy Sandage, she's ready to stand with Riess and answer the brash challenge from the Planck team. "The message was 'You guys are wrong.' Well, maybe," she says, chuckling. "We'll see." ■

Joshua Sokol is a journalist based in Boston.

Corrected 10 March 2017. See full text.

Published by AAAS